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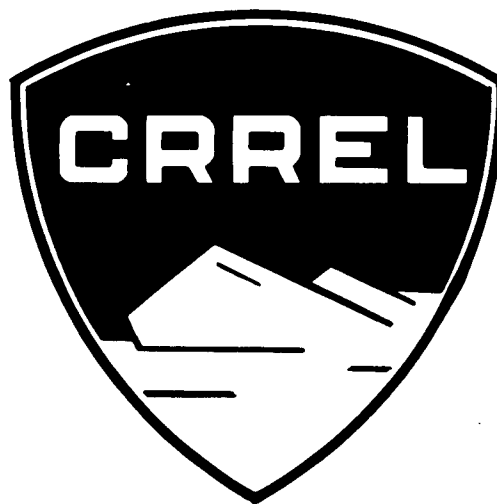
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Research Report 105

JANUARY, 1963

Vertical Migration of Particles in Front of a Moving Freezing Plane



U. S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY

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Vertical Migration of Particles in Front of a Moving Freezing Plane

by Arturo E. Corte


**U. S. ARMY COLD REGIONS RESEARCH
AND ENGINEERING LABORATORY
Hanover, New Hampshire**

PREFACE

This is one of a series of reports of work on USA CREEL subtask 5010.03141, Field and laboratory study of patterned ground.

The work was performed for the Materials Research Branch, Dr. Paul R. Camp, Chief, and the Research Division, James A. Bender, Chief. Mr. Robert Tien conducted most of the tests. SP5 Wayne J. Brule, and Mr. Allen R. Tice assisted in preparation of the report.

This report has been reviewed and approved for publication by the Commander, U. S. Army Materiel Command.


W. L. NUNCESSER
Colonel, Corps of Engineers
Commanding Officer
USA CRREL

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Department of the Army Project 8X99-27-001-03

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SUMMARY

A principle of particle segregation by freezing is presented. It is demonstrated experimentally by using a transparent freezing cabinet in which a sample of distilled water freezes from the bottom upward. In this way the freezing front line travels vertically and the particles are carried against gravity.

By using the same material with different shapes (glass beads and broken quartz or glass) it is demonstrated that an important factor in particle migration is the shape of the particle or its contact area with the interface. By testing other materials with different shapes and sizes, it is demonstrated that another important factor is particle size and rate of freezing. Fine particles migrate under a wide range of rates of freezing; coarser ones migrate at lower and more limited ranges of rates of freezing.

It is suggested that, for determining frost behavior of soils in permafrost regions, freezing from the bottom upward is a more reliable test than freezing from the top down. Freezing from the bottom more closely approximates freezing of the active layer above permafrost; also, friction with the cylinder testing wall is eliminated.

The implication of this principle in engineering and studies of soil genesis in cold regions is emphasized.

VERTICAL MIGRATION OF PARTICLES IN FRONT OF A MOVING FREEZING PLANE

by

Arturo E. Corte

INTRODUCTION

The first step in the investigation of a complex phenomenon is the isolation of important variables. The second step is the use of a suitable experimental setup which permits observation of the effect of such variables under controlled conditions. The third step is the formulation of a theory or a law which forecasts and controls the phenomenon.

This paper deals with the first and second steps.

The literature on frost effects in soils is generally concerned with the behavior of certain types of soils or kinds of minerals under varied conditions of moisture, temperature, density, size gradation, etc. It has been impossible to determine the effect of more isolated factors such as particle shape and contact area with the ice interface, however, because of the lack of a suitable freezing cabinet and a technique for contacting particles with the ice interface.

Investigation on particle migration by freeze-thaw cycles has been started recently. To date it has been demonstrated that, in heterogeneous soils, finer particles move away from the cooling front (Corte, 1961-1962), producing horizontal or vertical sorting depending on the position of the freezing plane. This migration of particles has a great implication in soil mechanics, soil genesis, and the behavior of vegetation in permafrost and cold regions.

In the study of the factors responsible for this migration, a special transparent cabinet was used, so that the effect of the interface movement on certain particle sizes and shapes could be observed. The present report deals particularly with the technique of contacting different particles with the ice-water interface, and with the effect of size, shape, and rate of freezing on particle migration.

Experimental procedure

The cabinet used in this experiment consists of two transparent Lucite cylinders 5 in. and 6 in. in diameter with a $\frac{1}{2}$ in. wall (Fig. 1). Between the two cylinders there is an air space $\frac{1}{2}$ in. thick. The lower part of the cylinders is screwed to a 1-in. thick aluminum plate, which produces a unidirectional freezing from the bottom upward. The inner 5 in. cylinder is filled with distilled water which freezes upward from the contact with the aluminum plate in such a way that a flat freezing line was obtained (Fig. 1). The cylinder was graduated in millimeters for measurement of the freezing-line height. The cylinders are covered by a wooden box 1 in. thick which encloses a heating tape. Rates of freezing from 0.2 to 7.0 mm/hr can be obtained by changing the voltage on the heating tape and placing the cabinet in a -5, -10, or -20°C cold room.

When the rate of freezing was known, the particles were put in contact with the interface. At the beginning of the experiment, particles were suspended from fine threads and held in position until the interface touched the particle. This method was tedious and slow and a more satisfactory 'seeding' method was developed:

The particles to be tested were washed several times with distilled water. In general, 50 g of particles were used, except that only 20 g of mica were used. A small beaker containing the particles and 50 cc of distilled water was placed at approximately the freezing point for several hours so that the particle temperature was close to that of the interface. Then the water containing the particles was poured into the cylinder, spreading the particles to form a uniform layer about 1 to 3 mm thick on top of the ice. The interface height was measured after seeding. When particles were carried about 1 cm by the interface they were siphoned off with a hose and the percentage of particles carried was

VERTICAL MIGRATION OF PARTICLES DURING FREEZING



Figure 1. Transparent freezing cabinet for freezing from the bottom upward.



Figure 2. Freezing cabinet in which three sizes of sand particles ranging from 0.1 to 7 mm in diameter were seeded close to the bottom. Fine particles were carried to the top and coarser ones were trapped by the ice close to the seeding position. Notice the stream of bubbles underneath the particles.

expressed on a weight basis. During the experiments it was observed that, if the particles are not removed, they will move continuously if the rate of freezing is constant or decreases. Figure 2 shows the migration of sand particles from 0.1 to 7 mm in diameter: While the coarser particles were trapped by the ice close to the seeding place, the finer particles migrated continuously 6 in. up to the top of the freezing cabinet.

The following materials were used: glass beads, broken glass (window), quartz crystals, calcite, rutile, shale, and mica. Glass beads, broken glass, and quartz crystals have the same density, but the contact area of the particle and interface is very small for glass beads and larger for quartz and broken glass. In this way it is possible to observe the effect of shape or interface contact area upon migration.

By using broken quartz and rutile, it is possible to observe the effect of density upon migration if the contact area is the same. The densities of the materials used are:

Glass (broken beads)	2.4 - 2.6
Quartz	2.5 - 2.6
Mica	2.6 - 3.1
Shale	2.6 - 3.3
Calcite	2.7
Rutile	4.1 - 5.3

Shale and mica have essentially the same density, but shale is 5 to 10 times thicker than mica, and therefore the pressure of shale on the interface is greater than that of mica. Both provide a larger contact area with the interface than the other materials; mica is smoother and has the largest contact area. Considering only the physical properties by comparing the behavior of mica and shale, we can obtain information on the effect of pressure of the particle and contact area with the ice.

The contact area between the particle and the ice increases in the following order: glass beads, broken glass, quartz, shale, and mica. The pressure of the particle on the interface is greatest for glass beads and smallest for mica flakes.

For the preparation of samples of quartz, calcite, and mica, characteristic crystal forms were chosen. The crystals were crushed in a mortar and then sieved on a shaker for 15 min through 1.000, 0.590, 0.290, and 0.149 mm sieves. The material retained in each sieve was used for the experiments. It was observed during the crushing of calcite that the big rhombohedral crystals broke into smaller ones of the same form. Without measurements of the surface areas it is possible to say that the contact area of calcite will be greater than that of glass beads and smaller than that of shale.

Experimental results

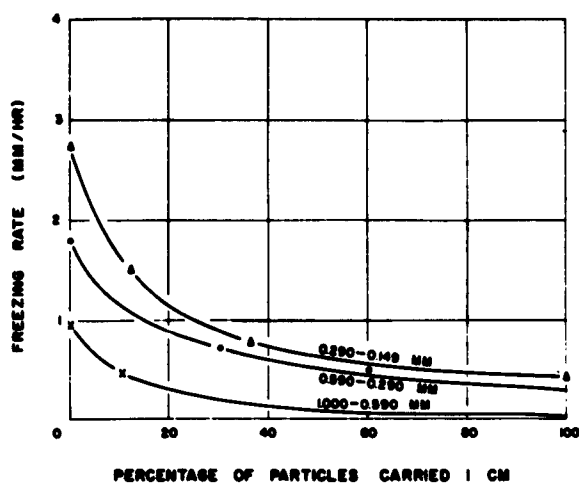
The migration of 0.149, 0.290, and 0.590 mm particles of broken glass, calcite, rutile, quartz, and shale is shown in Figures 3a - e. Because of the great migration of mica particles a large size of 1.0 mm was tested (Fig. 3f). Glass beads migrated least and the only values obtained were for 0.149 mm diam. In all curves plotted, fine particles exhibited greater migration than coarser particles of the same material.

Fine particles migrate under a wide range of freezing rates, and coarse ones migrate at a limited and low rate. At freezing rates less than 1 mm/hr all particles tend to migrate regardless of the shape and size.

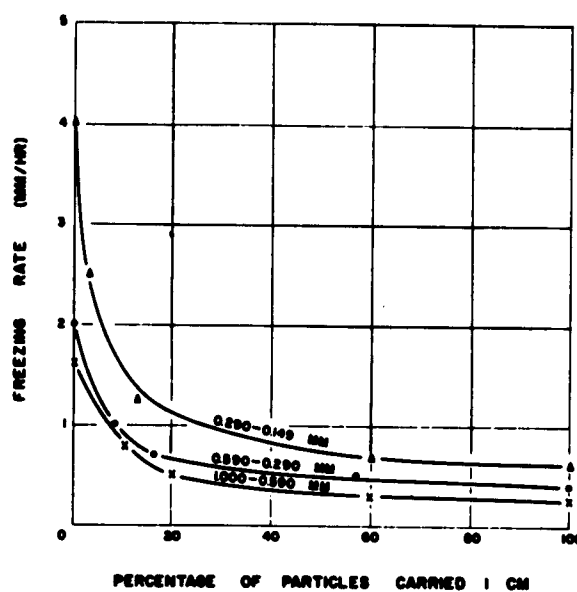
The migration of size 0.149 mm glass beads, broken glass, and quartz is shown in Figure 4a. Glass beads, with the smallest contact area, show the smallest migration. Quartz and broken glass particles of similar material, but with less sphericity and greater contact area, show a greater migration. Figure 4b shows the migration of size 0.149 mm calcite, rutile, quartz, shale, and mica. Calcite particles of rhombohedral shape have the smallest contact area and more weight per unit area with the interface. The contact area of rutile and quartz is not known; it is not possible to say yet if the smaller migration of rutile is caused by its greater density.

Shale and mica, with the largest contact area, exhibit the largest percentage of migration. Mica is 5 to 10 times thinner than shale, has the smallest weight per unit area on the interface, and exhibits the greatest migration.

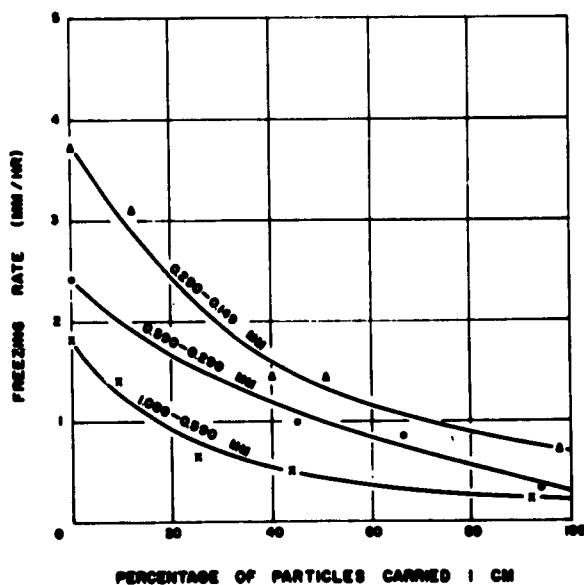
VERTICAL MIGRATION OF PARTICLES DURING FREEZING



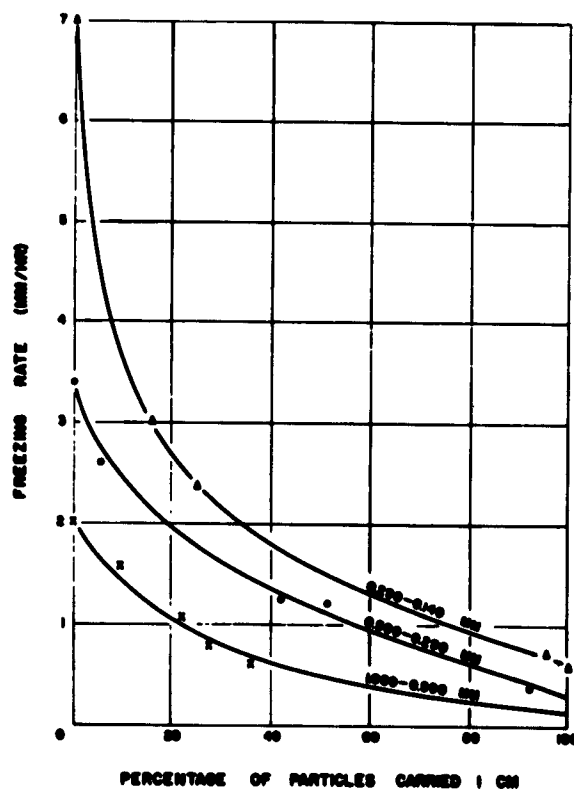
a. Broken glass.



b. Calcite particles.

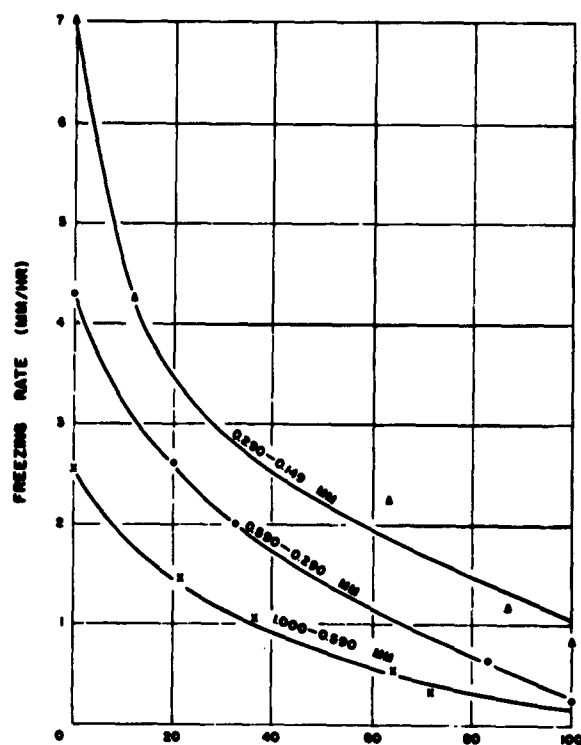


c. Rutile particles.



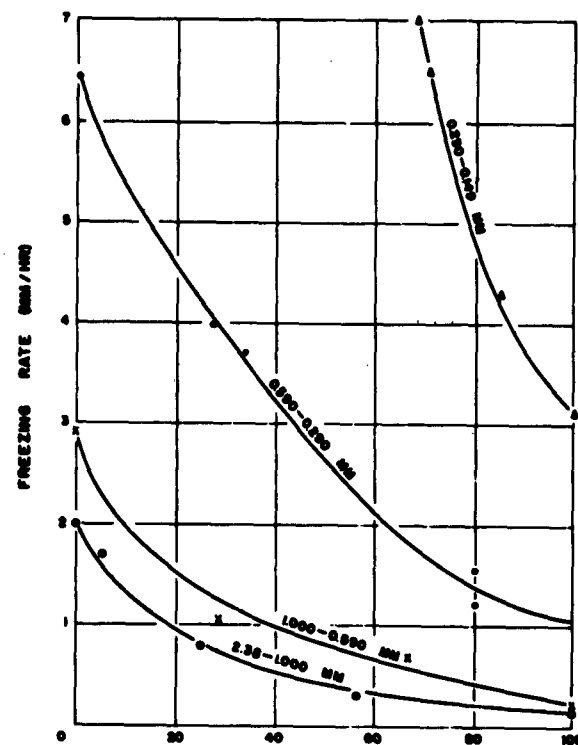
d. Quartz particles.

Figure 3. Percentage (by weight) of particles carried 1 cm in front of the freezing plane under different rates of freezing.



PERCENTAGE OF PARTICLES CARRIED 1 CM

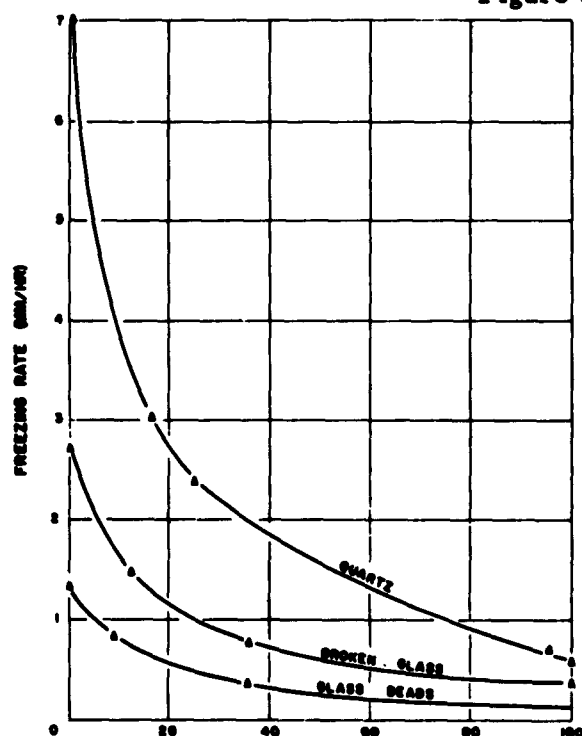
e. Shale particles.



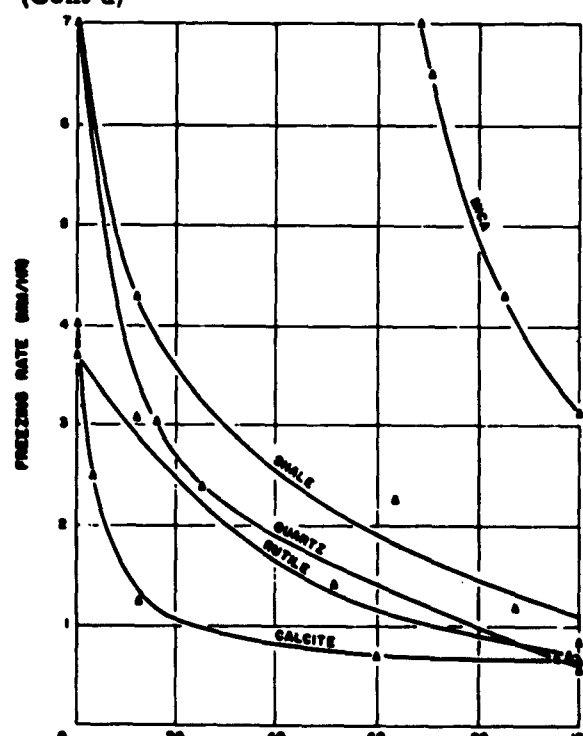
PERCENTAGE OF PARTICLES CARRIED 1 CM

f. Mica particles.

Figure 3. (Cont'd)



PERCENTAGE OF PARTICLES CARRIED 1 CM



PERCENTAGE OF PARTICLES CARRIED 1 CM

Figure 4. Percentage (by weight) of 0.149 mm particles carried 1 cm in front of the freezing plane under different rates of freezing.

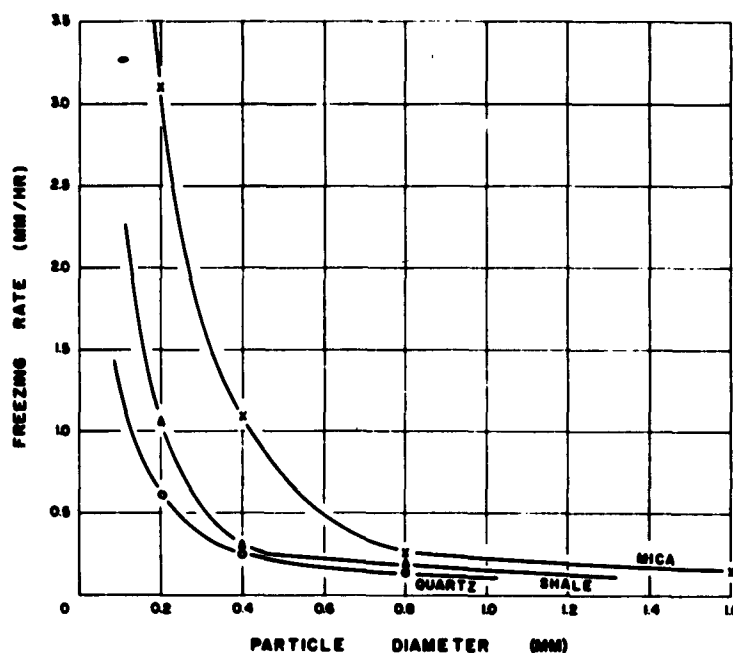


Figure 5. Freezing rates required for particles of different diameters to move continuously in front of the interface.

It is clear therefore that increasing the contact area of the particle while the size is constant causes the migration to increase. This is observed by comparing materials of the same composition, such as glass beads and broken glass, and by comparing materials of different composition, such as calcite, rutile, quartz, shale, and mica. It is clear that the pressure per unit area decreases as the contact area pressure increases.

A family of curves for different minerals can be made by using the rates of freezing at which all particles seeded are carried in front of the freezing plane. Figure 5 shows the rates of freezing required for all particles of different diameter to move continuously in front of the interface without being trapped by the ice. It is demonstrated that each particle size requires a certain rate of freezing in order to migrate continuously without being swallowed by the ice. This is clearly shown in Figure 2 where sand particles ranging from 1 to 7 mm in diameter were seeded on top of the interface. The smallest particles traveled 6 in. up to the top of the freezing cabinet while larger sizes were trapped by the ice closer to the seeding place. Figure 5 also shows that fine particles can move continuously in front of the interface under a wider range of freezing rates than coarser ones. The range of freezing rates is largest for mica, smaller for shale, and smallest for quartz.

For a particle to migrate, a layer of water must be continuously present between the particle and the ice front. This layer must be replenished, which is easy under small particles, but requires a large water flow for large particles. Since the thickness of the water layer is small, a low rate of freezing is necessary. In this way it is possible to explain why small particles migrate under a wide range of rates of freezing and larger particles require a low rate of freezing in order to migrate. A thin film of water between the ice lens and soil particles has been proposed by Taber (1930) as a necessary condition for the ice lens to grow.

During the experiments it was observed that migrating particles leave behind a trail or stream of bubbles. Figure 2 shows the bubbles left by the upward migration of sand particles ranging from 0.1 to 7 mm. In this figure it is also observed that coarser particles up to 7.0 mm diameter were lifted as much as 1 cm, leaving a bubble trail as wide as the particle. Particles that do not change orientation during their migration leave straight trails, but particles that rotate leave spiral trails.

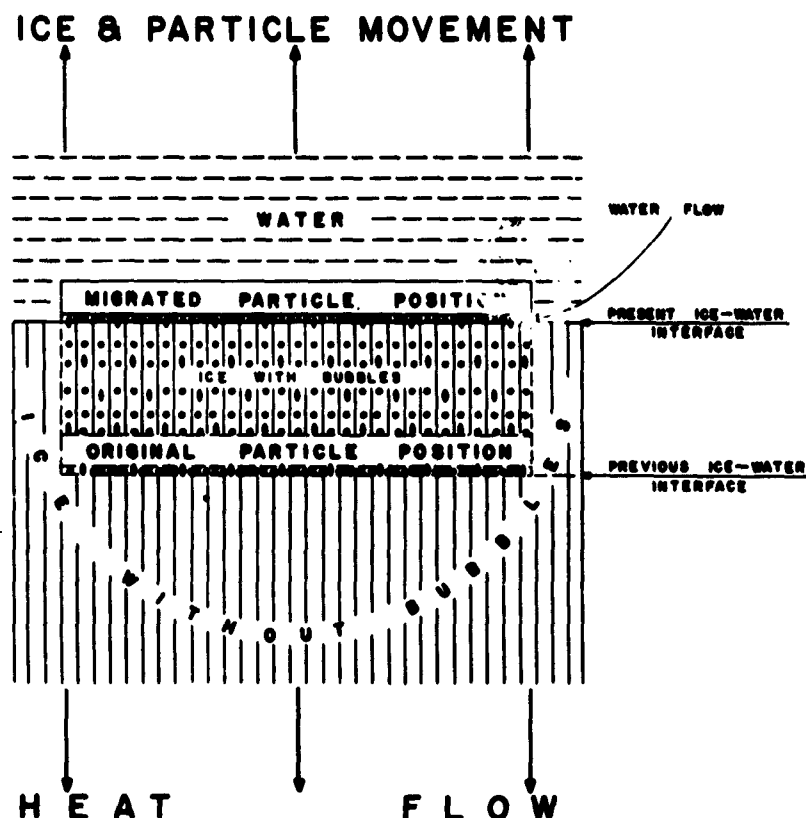


Figure 6. Upward migration of a particle in front of the freezing plane. Air bubbles are trapped under the particle; where there is no particle, air is expelled into the water.

The presence of bubbles can be explained in the following way (Fig. 6): as the ice front advances from the bottom upward, the air dissolved in the water is emitted because of the change of state. Bubble-free ice occurs where the air has not been blocked. If a particle is located in front of the moving ice, the air is trapped under the particle.

In the conventional tests for determination of frost behavior in soils the samples are frozen from the top down and friction between the soil and cylinder walls is a serious handicap. In the present setup friction is eliminated because freezing proceeds from the bottom and the part which moves is unfrozen. Besides, this way of freezing is more similar to conditions in permafrost areas where the active layer freezes from the bottom up as well as from the top down.

From the experimental data we may foresee a new criterion for the frost behavior of soils based on the range of freezing rates under which a certain amount of particles will migrate in front of the freezing plane. The larger the ranges of freezing rates, the more susceptible a soil will be to ice-lens formation.

Conclusions and recommendations

When water in contact with particles freezes, the ice tends to segregate the particles, pushing them in front of the moving freezing plane. The following results are available so far:

- 1) Particle migration is a function of the rate of freezing. For each particle size, freezing must be a certain rate in order to migrate continuously without being trapped by the ice. Fine particles can move under a wide range of rates of freezing;

coarser ones move at lower and more narrow ranges of rates of freezing. With freezing rates lower than 0.1 mm/hr, particles larger than 1.0 mm can be lifted. Such freezing rates are more likely to occur in nature. At low rates of freezing all particles tend to migrate, regardless of size, shape, and density.

2) Increasing the contact area, relative to weight, of a material increases the migration of particles.

3) Each particle moves upward, frequently leaving behind a stream of air bubbles. These bubbles are formed when the dissolved air in the water is expelled during the change of state. When a barrier such as a particle is in front of the expelled air, bubbles accumulate at the barrier wall (particle surface) and are trapped in the ice.

4) It is postulated that for the particle to migrate, a layer of water between the ice front and the particle is necessary. This water layer must be continuously replenished as the ice advances moving the particle ahead. When the water in this layer freezes more rapidly than it is replenished, the particles are trapped by the ice and do not migrate.

These basic experiments are considered of importance for: 1) the explanation of sorting in soils subjected to freezing and thawing cycles; 2) a better understanding of frost effects in soils for construction and agriculture; 3) the explanation of ice layers in organic and inorganic active layers and permafrost. Experiments must be performed to demonstrate the validity of this principle in organic deposits.

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- Taber, S. (1930) The mechanics of frost heaving, Journal of Geology, vol. 38, p. 303-317.

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